Experiences in the Practice of Design of Experiments at NASA

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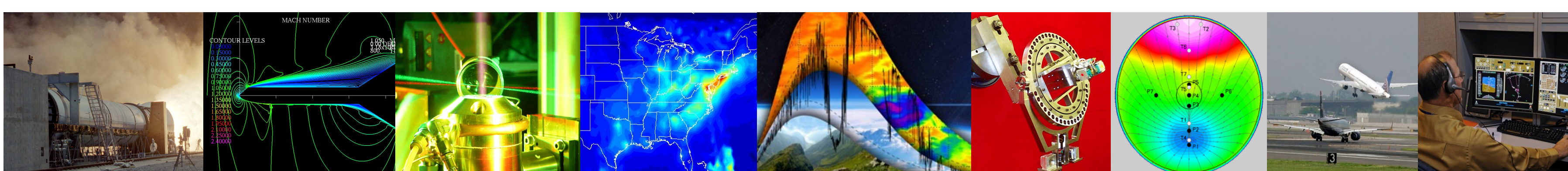
Design of Experiments Course Guest Lecture



NASA Langley Research Center

- One of 10 NASA Centers located in Southeastern Virginia
- Established in 1917 as first civilian aeronautics laboratory in the U.S.
- Initial home of the first astronauts, Mercury 7

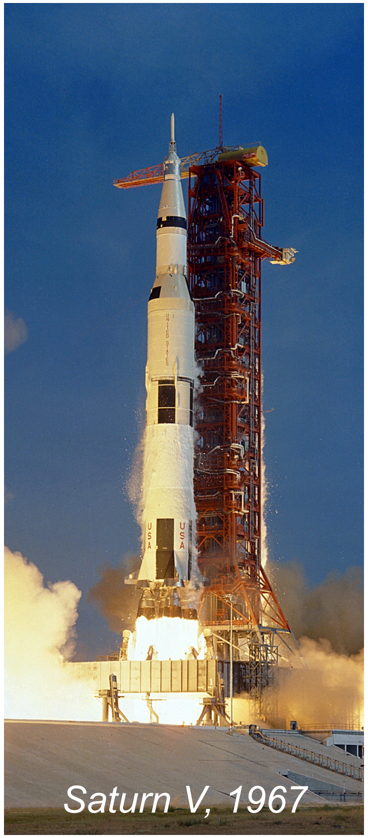
Today, we focus our research on technical challenges in:

- Space Exploration
- Aeronautics and Air Transportation
- Earth and Planetary Science

Aerospace and Statistical Timeline


Wright Flyer, 1903

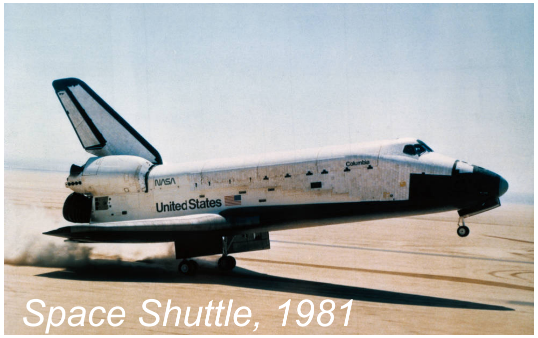
NASA Formed, 1958


Saturn V, 1967


Apollo 11, 1969

"…most of the statistical work is performed by engineers and scientists, some well trained in statistics and others having only a passing acquaintance with the subject…. " [1]


Variable Density Tunnel, 1921



Space Shuttle, 1981

Fisher, DOE, 1920's → Box, RSM, 1951 → Deming, Taugchi, Quality, 1980's

[1] Rubin, E. (1966) "Some Statistical Applications in the Apollo Program." *The American Statistician*, 20 (4), pp. 32-34.

An Engineer's Statistical Awakening

- **Traditionally, engineers lacked relevant, applicable, practical courses in statistics (*that's me*)**
  - **Engineers are generally trained to "fear" uncertainty**

- **In 1999, I stumbled upon a 1980 NASA report written by a visiting statistics professor with "radical" ideas that promised significant schedule and cost benefits.**

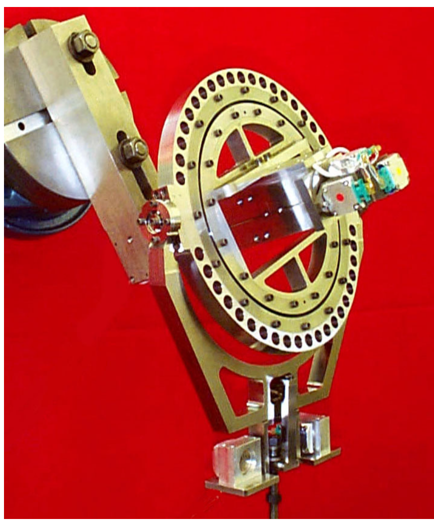
<u>A few of those "radical" statistical concepts</u>

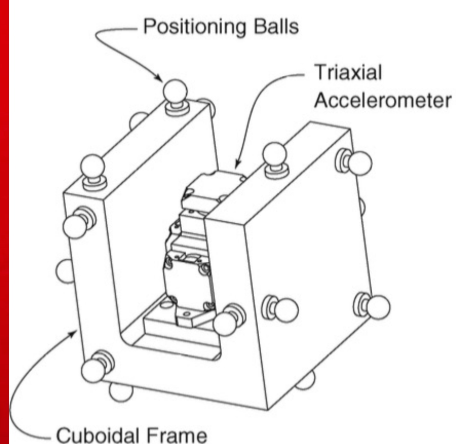
- **Experimental design starts with questions, not data**
- **Factorial experiments are efficient, not chaotic**
- **Modeling involves estimation, more than plotting data**

Discovered "new" powerful statistical techniques to efficiently learn and gain deeper insights,
Design of Experiments (DOE)

Measurement System Characterization

Improving aerospace research measurement systems quality

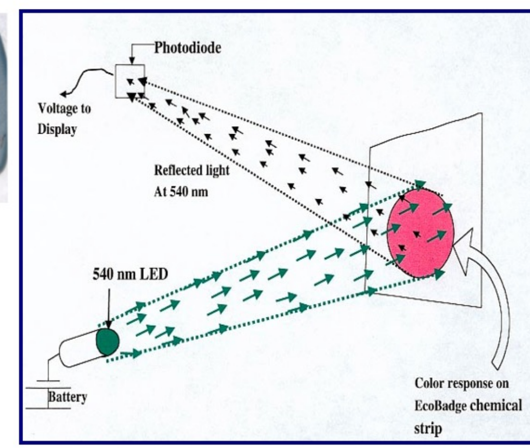




Parker, Morton, Draper, Line (2001), “A Single-Vector Force Calibration Method Featuring the Modern Design of Experiments,” *AIAA 2001-0170*.

Parker and Finley (2007), “Advancements in Aircraft Model Force and Attitude Instrumentation by Integrating Statistical Methods,” *AIAA Journal of Aircraft*.

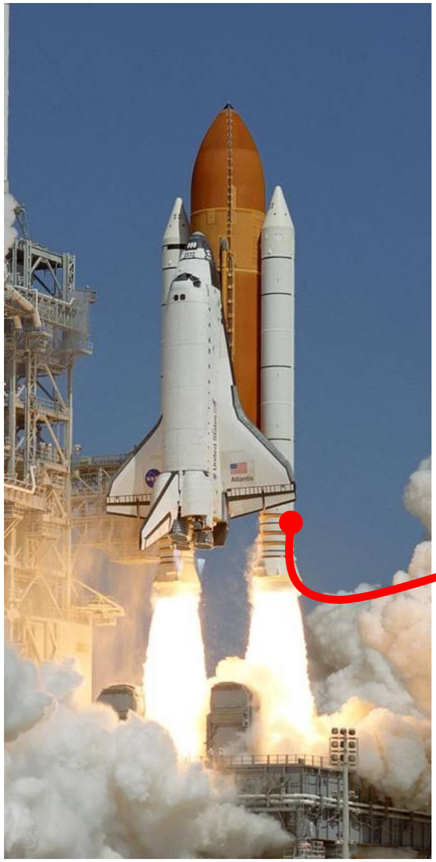
Increasing accessibility and participation in climate monitoring education



Pippin, et al. (2007), “Improvements to the Passive Ozone Measurement System Used by GLOBE Schools,” *American Geophysical Union Annual Conference.*

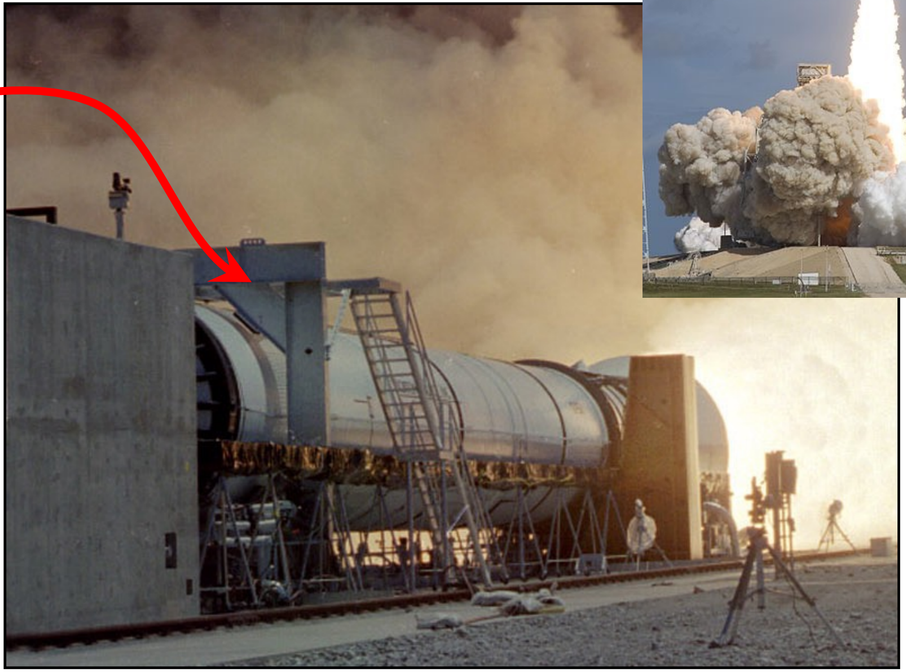
First Agency-Level DOE Demonstration

Shuttle

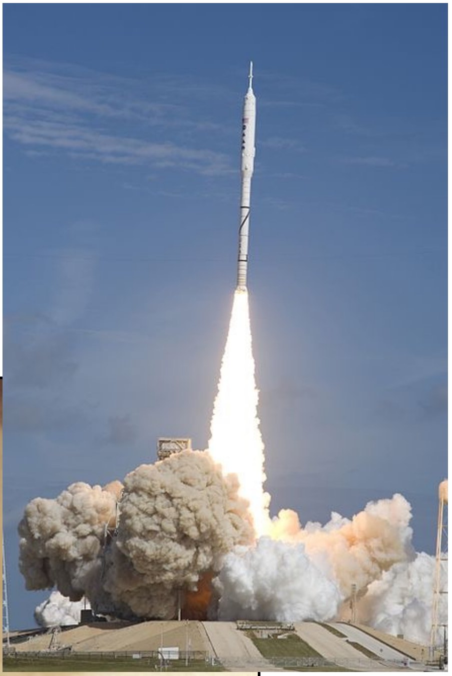


Ares I

Full-Scale Static Firing



Flight Test



Contributors: Gentz, Roberts, Parker, Rhew, Jones, McLennan, Nester, Freeman, Vining, 2006

Aerospace Wind Tunnel Testing

Characterizing aerodynamic performance of complex aircraft configurations

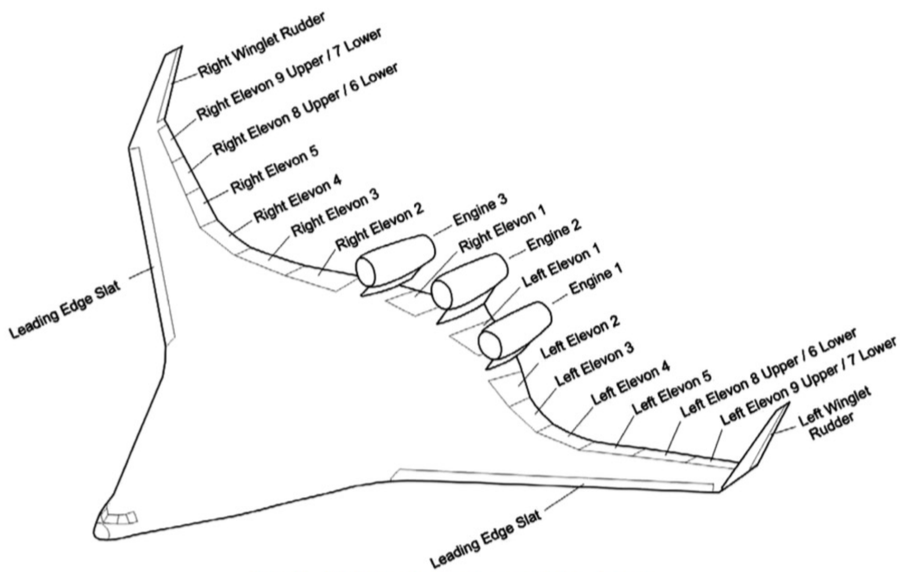


Fig. 2 BWB configuration control surfaces.

Landman, et al. (2007), "Response Surface Methods for Efficient Complex Aircraft Configuration Aerodynamic Characterization," *Journal of Aircraft*, 44, (4)

Powered test article of rotorcraft for computational model validation

Overmeyer, et al. (2015), "Case Studies for the Statistical Design of Experiments Applied to Powered Rotor Wind Tunnel Tests," AIAA 2015-2713

Practicing Design of Experiments Starts with Questions, not Data

Heilmeier's preflight checklist for successfully launching a project
"to curb and clarify both the enthusiasm of the researchers and to evaluate the resource demands of the project managers"

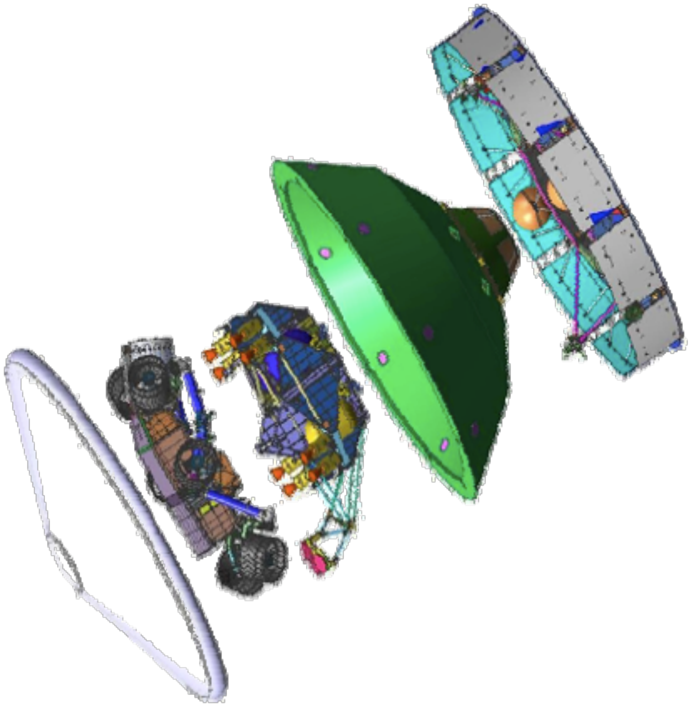
- **What are we seeking to learn?**
  - Are the objectives quantifiable, detectable, measurable?
  - What is the impact if you we successful?
- **How well do we need to know?**
  - How much risk are we willing to accept in being wrong?
  - What are the consequences if we are wrong?
- **Are the resource demands defendable to meet our objectives?**

Questions apply recursively throughout project life-cycle, and vertically from component testing up to vehicle design.

Hunter, W.G. (1981) "The Practice of Statistics: The Real World Is an Idea Whose Time Has Come," *The American Statistician*

Shapiro (1994) "George H. Heilmeier," *IEEE Spectrum*

Mars Planetary Entry, Descent, and Landing

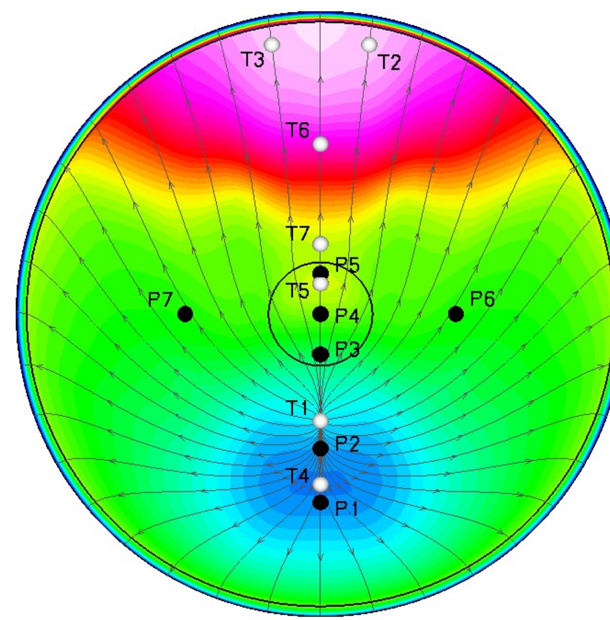


Objective: Reduce uncertainty in pre-flight landing ellipse estimation

Develop a measurement system to enable trajectory reconstruction of Mars entry to refine computational models

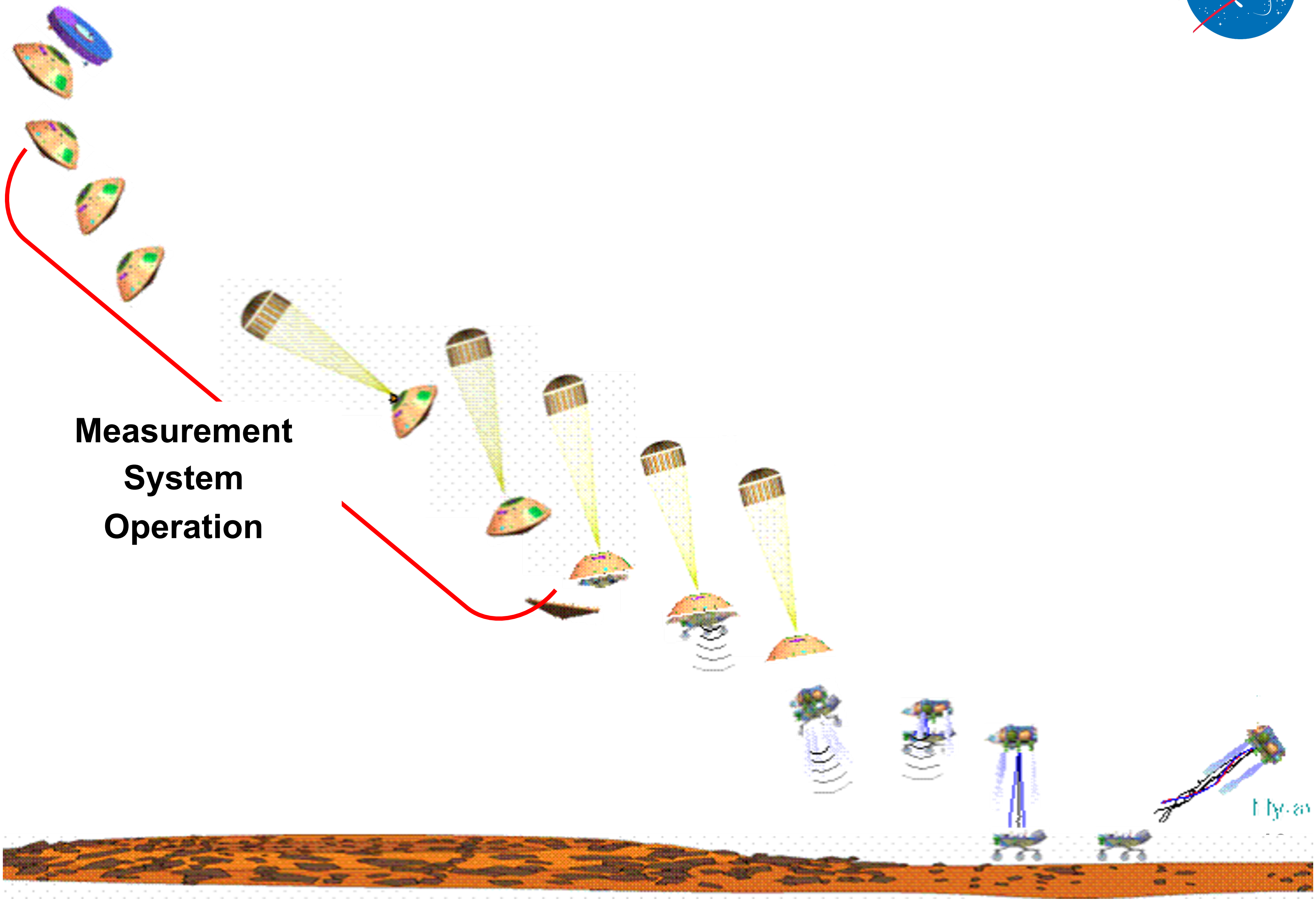
Measurement System Characterization

- **System of pressure sensors and electronics**
- **Pressures vary spatially across the heat shield and temporally throughout entry**
- **Temperatures conditions vary at start of entry and across the heatshield during entry**



Commo and Parker (2012), "Statistical engineering perspective on planetary entry, descent, and landing research," *Quality Engineering*

Entry, Descent, and Landing Timeline



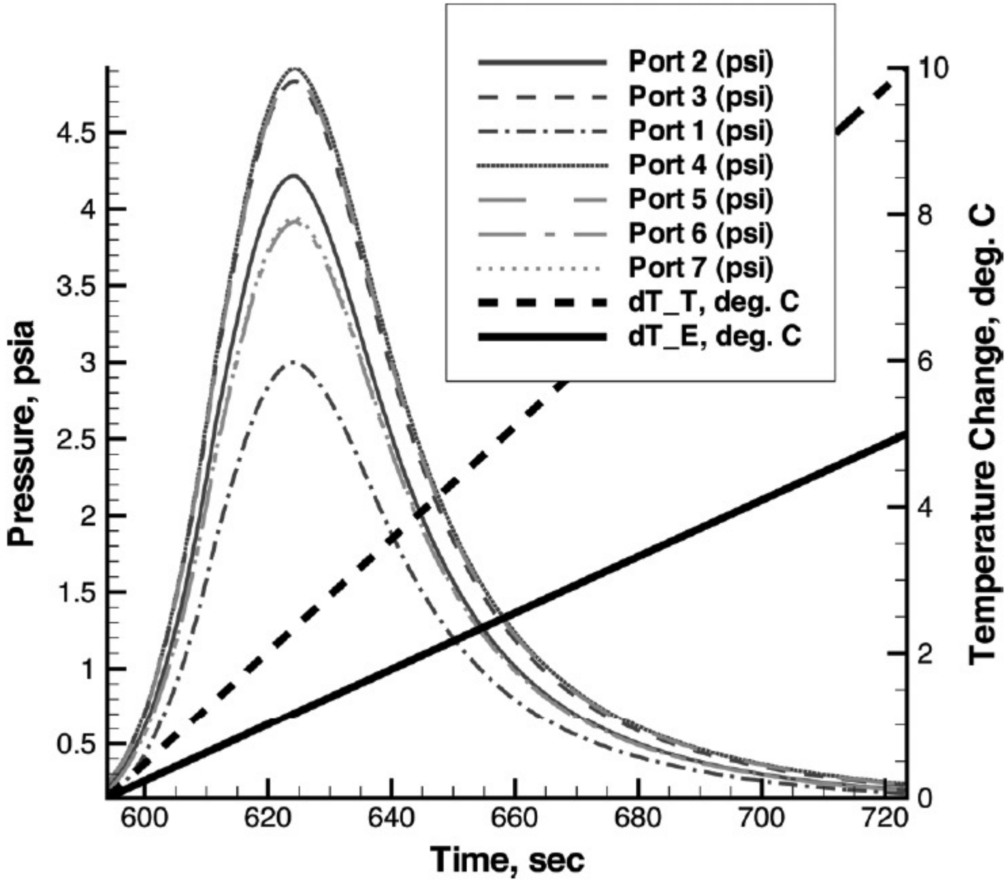
Experimental Design Factors

Characterization Design Space

Pressure	0 to 5 psia
Temp. Sensor	-120 to -60 deg.C
Temp. SSE	-20 to +55 deg.C

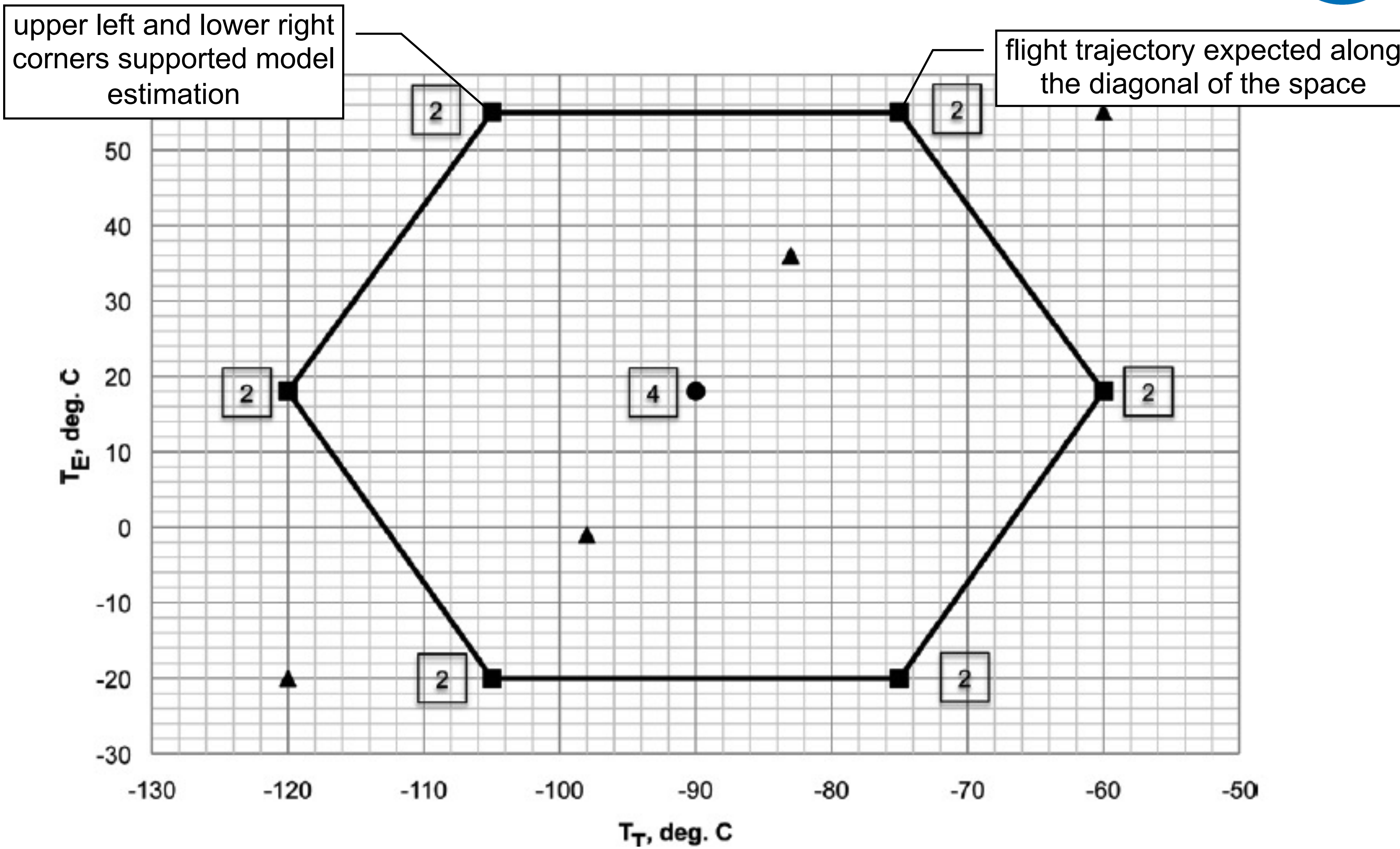
Sensor – multiple pressure transducers

SSE – signal support electronics form the data acquisition system (DAS)



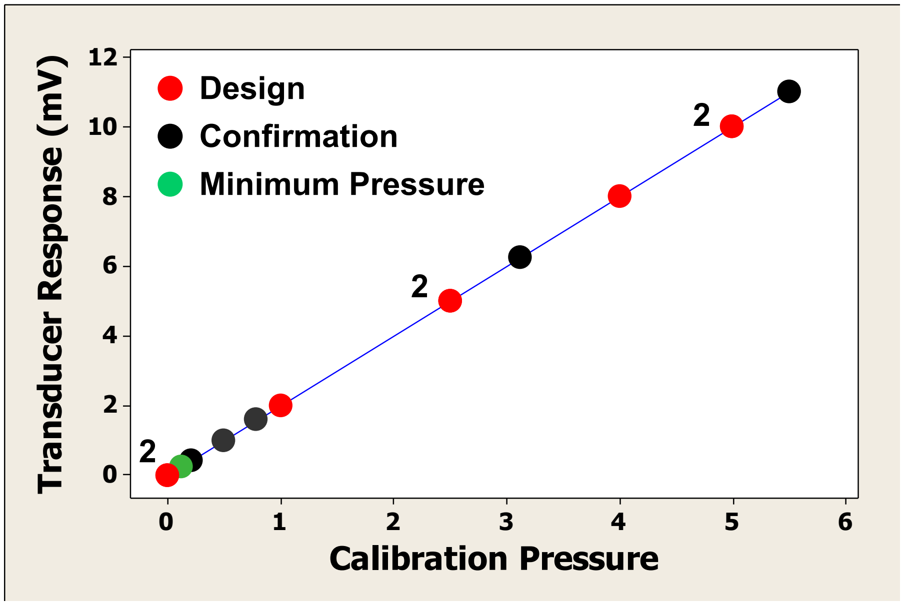
- **Temperatures vary between DAS and sensor locations (start and entry)**
- **Pressure varies across port locations**

Temperature Design Space



- **Superimposed designs to support multiple objectives**
  - **Model estimation, Confirmation, and Flight Trajectory**

Pressure Design Space



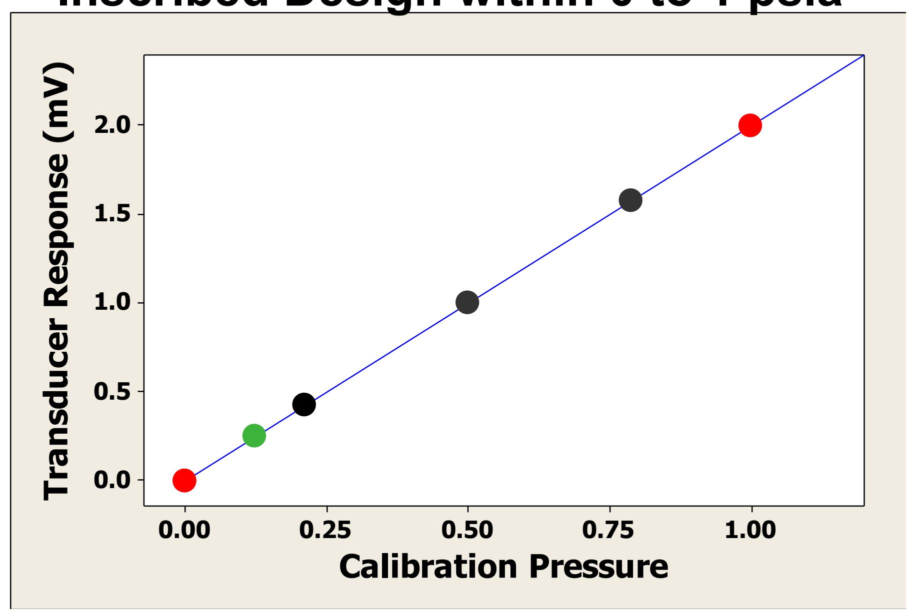
Allocation of Design Points

- 0-5 psia calibration (8)
- 0-1 psia low-end calib./conf. (3)
- 0.12 psia confirmation (1)
- 5.5 psia max confirmation (1)
- random conf. at mid-range (1)

Split-Plot Design, Nested randomization

- Once a temperature combination is set, pressure settings are completely randomized

Inscribed Design within 0 to 1 psia



Numbers indicate replicated design points

Mathematical Model

ability to update and estimate in flight

Primary Sensitivity Coefficient

zero intercept adjustments as a function of temperature

$$V = \beta_0 + \beta_1 P + \beta_2 T_{sensor} + \beta_3 T_{SSE}$$

second-order effect of pressure (non-linearity)

$$+\beta_{11} P^2 + \beta_{22} T_{sensor}^2 + \beta_{33} T_{SSE}^2$$

second-order effects of temperature on intercept

$$+\beta_{12} P x T_{sensor} + \beta_{13} P x T_{SSE}$$

sensitivity adjustments as a function of temperature

$$+\beta_{23} T_{sensor} x T_{SSE} + \varepsilon$$

assumed negligible based on system knowledge

Interpretation and Translation into the Subject-Matter Experts' Nomenclature is Vital

Model Development and Application

Characterization Model Developed on Earth in Environmental Simulation Laboratory

$$V = f\left(P, T_{sensor}, T_{SSE}\right)$$

Inverse Relationship used to Estimate Pressure During Mars Entry

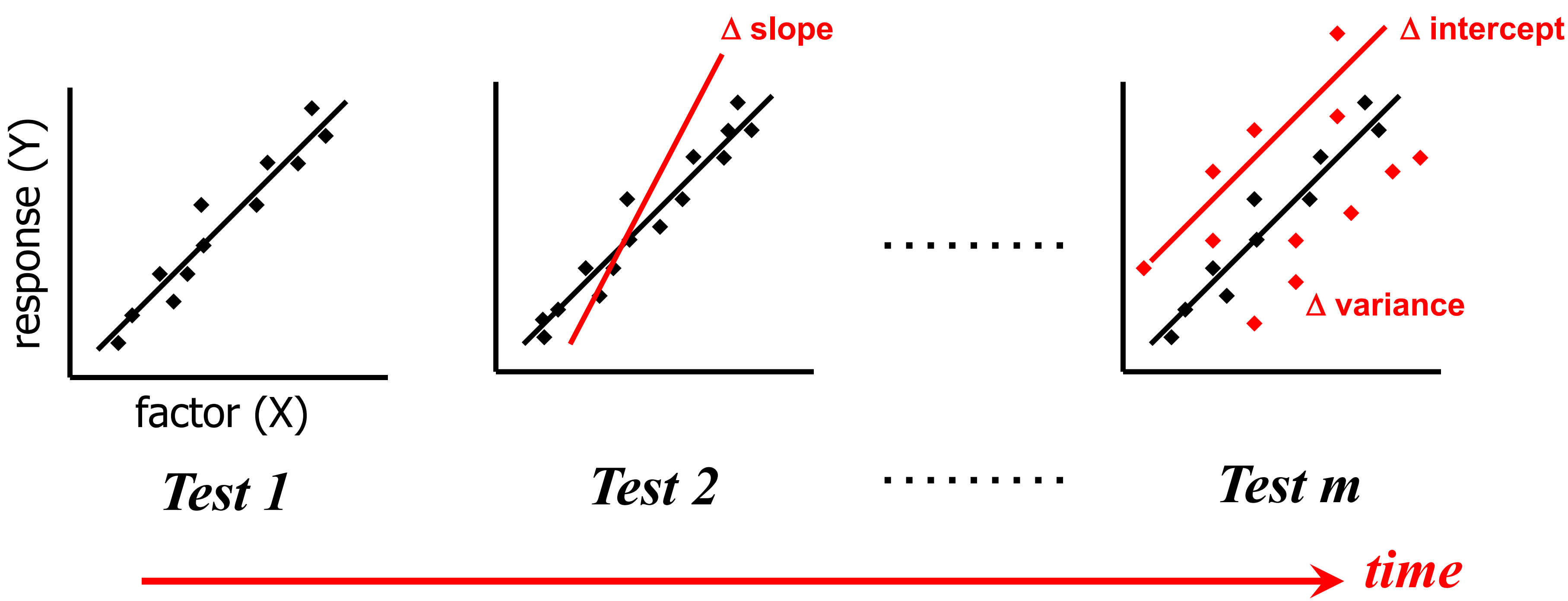
$$\hat{P} = f\left(V, T_{sensor}, T_{SSE}\right)$$

Inverse Model includes Estimated Uncertainty that Influences Flight Reconstruction Fidelity

Calibration Model Stability

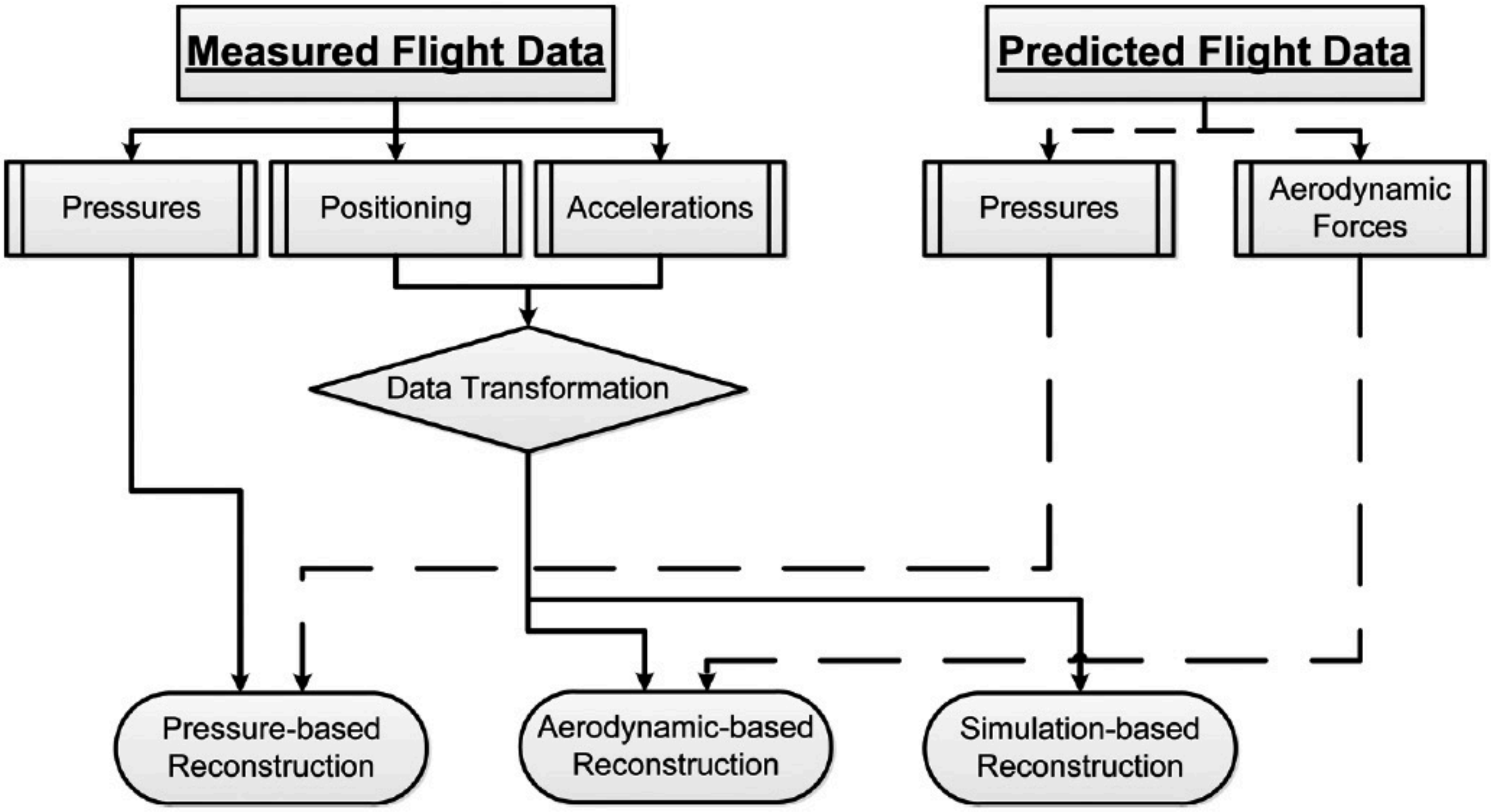
- **Stability tests are performed periodically to monitor the calibration model coefficients, not the raw data**

$$V = \boxed{\beta_0} + \boxed{\beta_1} P + \beta_2 T_{sensor} + \beta_3 T_{SSE} + \boxed{\beta_{11}} P^2 + \beta_{22} T_{sensor}^2 + \beta_{33} T_{SSE}^2$$
$$+ \beta_{12} P x T_{sensor} + \beta_{13} P x T_{SSE} + \beta_{23} T_{sensor} x T_{SSE} + \boxed{\varepsilon}$$



Conceptual Simple Linear Example

Models Integrated into Flight Reconstruction



Concluding Remarks

- **The practice of DOE relies on effective multi-disciplinary collaboration and the art of translating statistical concepts into subject-matter vernacular**
- **Infusing statistical DOE at NASA has influenced aerospace research and development, over the past 25 years**
- **Successful demonstrations have resulted in broader adoption of DOE philosophy and depth in DOE discipline expertise**